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3D energy deposition measurements with the GEMPix detector in a water phantom for hadron therapy

J Leidner

European Organization For Nuclear Research

M Ciocca

Fondazione CNAO

Stuart George

University of Wollongong, spg085@uowmail.edu.au

A Mirandola

Fondazione CNAO

Fabrizio Murtas

CERN

See next page for additional authors

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Abstract

In this paper we present 3D measurements of the energy deposition by a clinical carbon ion beam in a water phantom. Conventionally, these measurements are performed with an array of ionization chambers and used for quality assurance. The spatial resolution is typically not better than 5 mm. We used the GEMPix, a gaseous detector with a highly pixelated readout and much better spatial resolution. The GEMPix was obtained by coupling a triple Gas Electron Multiplier (GEM) to a quad Timepix ASIC with 512x512 pixels and 55µm pitch. The Bragg curve, 2D images of the beam and a 3D reconstruction of the energy deposition are obtained from a single depth scan performed in approximately 15 minutes. A separate linearity check was also performed. The detector response is well linear and the measured Bragg curve is very smooth with uncertainties of a few percent. 3D energy deposition measurements in a water phantom with the GEMPix provide better spatial resolution than conventional devices. Systematic differences in the Bragg curve in comparison to the reference one are still too large for clinical use but work on several improvements is on-going.

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Authors

J Leidner, M Ciocca, Stuart George, A Mirandola, Fabrizio Murtas, A Rimoldi, Marco Silari, and A Tamborini

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3D energy deposition measurements with the GEMPix detector in a water phantom for hadron therapy

J. Leidner,^{a,b,1} M. Ciocca,^c S.P. George,^{a,d,2} A. Mirandola,^c F. Murtas,^{a,e} A. Rimoldi,^{f,g}
M. Silari^a and A. Tamborini^{f,8}

^aCERN, 1211 Geneva 23, Switzerland

^bPhysics Institute 3B, RWTH Aachen University, 52074 Aachen, Germany

^cFondazione CNAO, 27100 Pavia, Italy

^dUniversity of Wollongong Centre for Medical Radiation Physics, Wollongong, NSW 2522, Australia

^eINFN-LNF, 00044 Frascati, Italy

^fUniversity of Pavia-Department of Physics, 27100 Pavia, Italy

^gINFN Section of Pavia, 27100 Pavia, Italy

E-mail: johannes.leidner@cern.ch

ABSTRACT: In this paper we present 3D measurements of the energy deposition by a clinical carbon ion beam in a water phantom. Conventionally, these measurements are performed with an array of ionization chambers and used for quality assurance. The spatial resolution is typically not better than 5 mm. We used the GEMPix, a gaseous detector with a highly pixelated readout and much better spatial resolution. The GEMPix was obtained by coupling a triple Gas Electron Multiplier (GEM) to a quad Timepix ASIC with 512×512 pixels and 55 µm pitch. The Bragg curve, 2D images of the beam and a 3D reconstruction of the energy deposition are obtained from a single depth scan performed in approximately 15 minutes. A separate linearity check was also performed. The detector response is well linear and the measured Bragg curve is very smooth with uncertainties of a few percent. 3D energy deposition measurements in a water phantom with the GEMPix provide better spatial resolution than conventional devices. Systematic differences in the Bragg curve in comparison to the reference one are still too large for clinical use but work on several improvements is on-going.

KEYWORDS: Dosimetry concepts and apparatus; Instrumentation for hadron therapy; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc)

¹Corresponding author.

²Now at the University of Houston, Department of Physics, Houston, TX 77204, U.S.A.



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1 Introduction

Hadron therapy is progressively spreading worldwide since the first clinical setup in the early 1990s [1], with more than 170,000 patients treated as of the end of 2016 [2]. Improved detectors for dose measurements and quality assurance are necessary [3]. In this work we used the GEMPix [4] — a gaseous detector with a 55 μm pitch pixelated readout — to measure the 3D energy deposition of carbon ion beams in a water phantom. In this way the Bragg curve, 2D images of the beam at any given depth and a 3D reconstruction of the energy deposition are obtained. Conventional systems typically consist of arrays of ion chambers with a spatial resolution not better than some 5 mm, which is much larger than the pixel pitch of the GEMPix. First measurements with the GEMPix in a water phantom at CNAO, the Italian National Centre for Oncological Hadron Therapy [5], are presented. The GEMPix has also been used in 2D imaging of energy deposition in radiotherapy [6]. It is also possible to use an optical readout with GEMs [7, 8] and [9].

2 The setup

2.1 The GEMPix

The GEMPix is a novel detector obtained by coupling two technologies developed at CERN, namely a small triple Gas Electron Multiplier (GEM) detector ($2.8 \times 2.8 \times 0.3 \text{ cm}^3$ active volume) to a quad Timepix [10] ASIC with 262,144 pixels of $55 \times 55 \mu\text{m}^2$ area for readout (figure 1).

Particles like carbon ions are detected by ionization in a gas detection volume behind a thin Mylar entrance window approximately 20 μm thick. A continuous flow of an $\text{Ar}:\text{CO}_2:\text{CF}_4$ (45:15:40

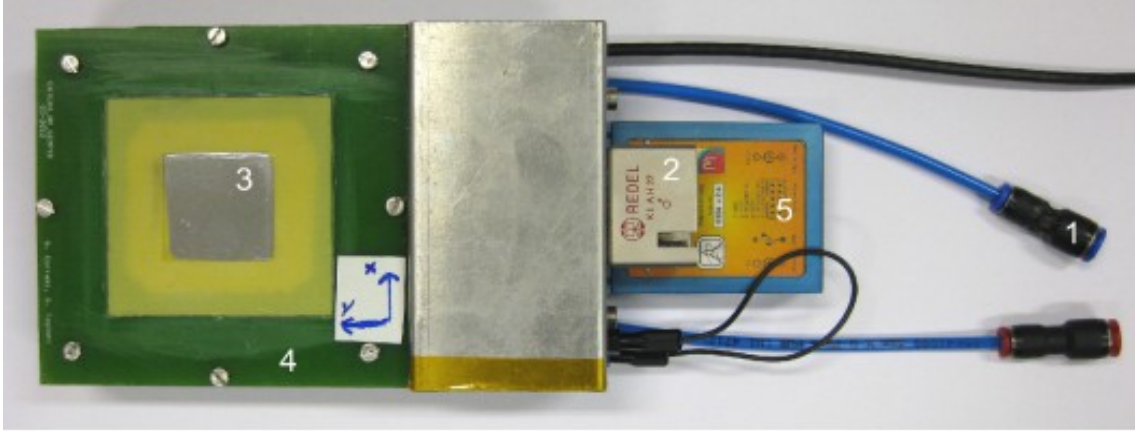


Figure 1. [11]: the GEMPix detector: (1) external gas supply, (2) external HV connector, (3) Mylar entrance window, (4) frame to hold the GEM foils, (5) FITPix readout.

ratio) gas mixture¹ is supplied externally at a rate of 5 l/h. The electrons produced by the ionization are driven by an applied high voltage towards three layers of GEM foils, where multiplication takes place due to the high voltage of approximately 320 V per GEM. The resulting electrons are then detected by the quad Timepix ASIC and read out by the FITPix readout [13] with the Pixelman software package [14]. The chosen readout mode, time over threshold (TOT), provides a value proportional to the deposited charge by the primary particle. A more detailed description of the GEMPix can be found in refs [4] and [11].

2.2 Experimental setup at CNAO

Measurements were performed at CNAO, the Italian Centre for Oncological Hadrontherapy, which is equipped with a synchrotron delivering scanning proton and carbon ion beams to three treatment rooms. One of the available fixed horizontal beam lines was used. The GEMPix was placed inside a watertight PMMA box mounted on the 3D positioning system of the motorized water phantom routinely used for Quality Assurance (MP3-P, PTW Freiburg, Germany) [15]. In particular, the depth axis has a range of movement of more than 350 mm and a positioning reproducibility of ± 0.1 mm. Figures 2 and 3 show the setup. The sensitive area of the GEMPix was facing directly the beam. The CNAO synchrotron provided carbon ions (C^{6+}) with kinetic energies of 280 MeV/u or 332 MeV/u with either a pencil beam (single beam spot) or scanned field. Pencil beams were used for all depth scans while a scanned field was only used for the linearity study presented in figure 4. The beam intensity was set to the smallest possible intensity of $2 \cdot 10^6$ particles per second during spill to avoid saturation in the detector. This beam intensity is approximately a factor 25 smaller than the maximum beam intensity of a carbon ion beam at CNAO and was achieved using the F10 degrader in clinical settings. Beams for clinical commissioning were characterized for each of the available beam currents including F10 and beam properties do not depend on the

¹Other, cheaper gas mixtures such as Ar:CO₂ could be used instead. However, the fast drift velocity of Ar:CO₂:CF₄ is needed in other applications of the GEMPix to reduce the lateral electron diffusion and therefore to increase the cluster analysis performance [12].

beam intensity [5, 15]. Therefore, the conclusions drawn in the present paper on the relative dose measurements also hold for larger beam intensities since the spatial distribution of the dose does not depend on the beam intensity. Typically, spill duration was 1 s, followed by a pause of 3 s [5]. Approximately, the beam profiles in both dimensions had Gaussian distributions with a sigma of 2 mm in air just before entering the water phantom. Reference measurements of the beam intensity were performed during the whole experiment with the Dose Delivery System (DDS) of CNAO [16], mainly consisting of two large-area beam monitors mounted in the nozzle. In this way the GEMPix data were normalized to the delivered dose, since the beam intensity cannot be assumed stable during a depth scan. The DDS provides integrated dose values every 50 ms.

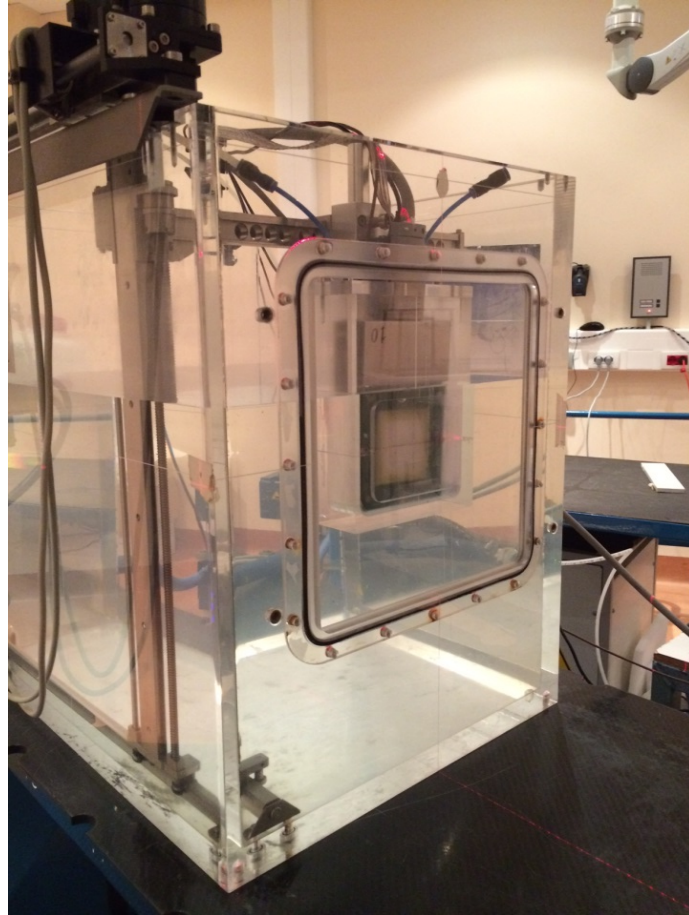


Figure 2. The GEMPix mounted on the water phantom in one of the treatment rooms.

3 Measurements and results

3.1 Linearity check

In order to check the linearity of the GEMPix response, the number of particles delivered over a flat field was varied. The check was performed with a $60 \times 60 \text{ mm}^2$ scanned field and 280 MeV/u carbon ions. The field size was chosen larger than the sensitive area of the detector to neglect possible edge effects of the field. Figure 4 shows that the response is linear over more than a factor of five in beam

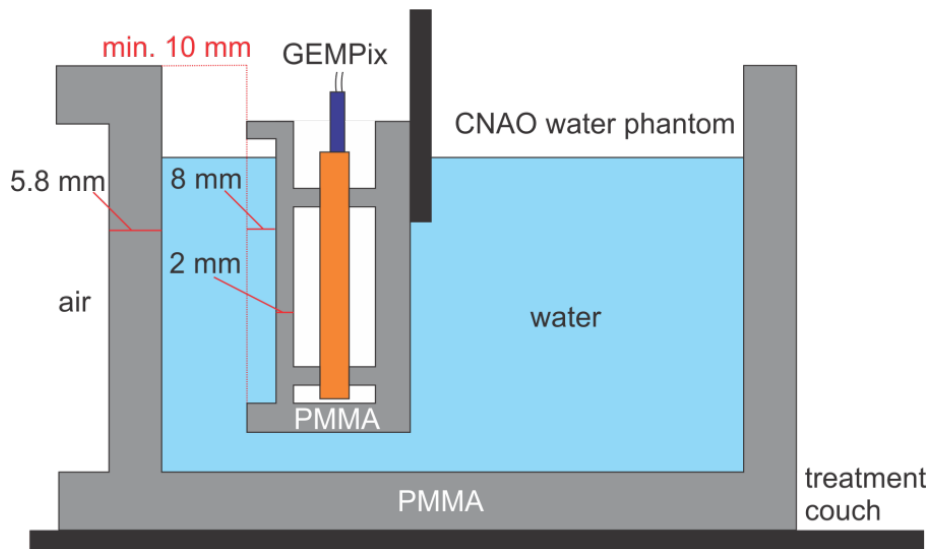


Figure 3. Schematic drawing of the setup (not to scale). The GEMPix is placed inside a watertight PMMA box mounted on the positioning system of the phantom. The beam enters from the left. The distance between entrance window and GEMPix box can be varied to scan along the beam axis.

intensity, matching approximately the expected peak-to-plateau ratio in a carbon ion Bragg curve. An estimated 1% uncertainty on the GEMPix TOT (Time Over Threshold, which is proportional to energy) integral is applied, which is approximately the same as measured during the depth scans.

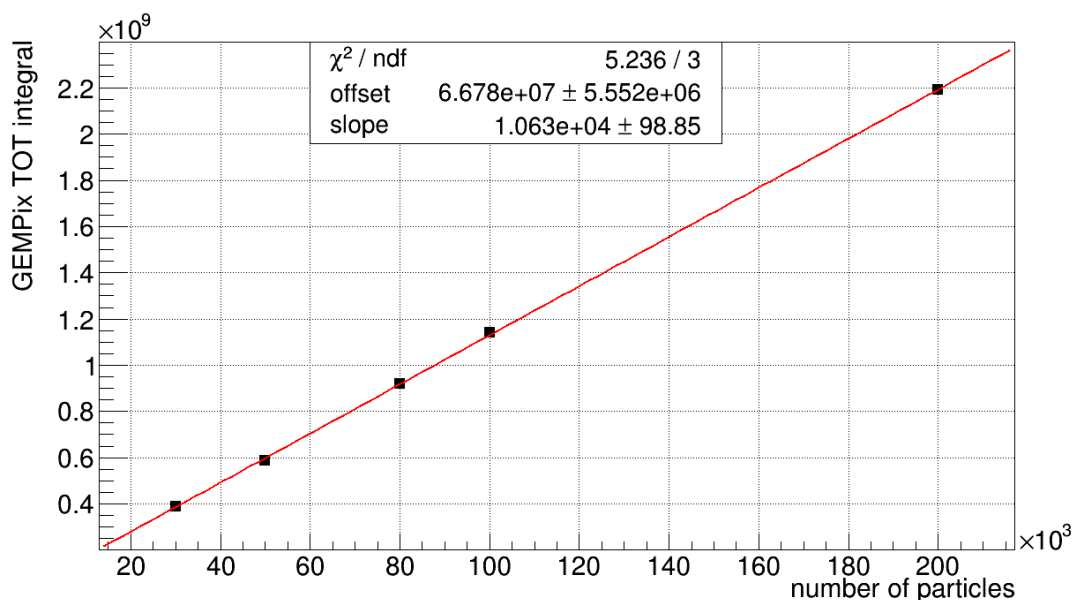


Figure 4. The detector shows a linear response when the total number of delivered particles varies from $3 \cdot 10^4$ to $2 \cdot 10^5$. Uncertainties are smaller than the data points.

3.2 Depth scans

The GEMPix data acquisition is frame based; a frame length of 50 ms was used. A significant dead time of 100 to 300 ms occurred due to read out and reset times of the pixels. The position of the GEMPix, i.e. its depth in water, was varied from the minimum depth — approximately 26 mm water equivalent thickness — to a position well beyond the Bragg peak. The distance in between positions was smaller in the Bragg peak region to better follow the rise and fall of the energy deposition. Typically, 30 positions per depth scan were chosen to obtain a well measured Bragg curve. The GEMPix stayed 30 s at each position which results in about 15 minutes for a complete depth scan. Each frame of the GEMPix provides a 2D image of the energy deposition in the pixels. Figure 5 shows typical frames for different depths in water.

In order to obtain the Bragg curve, for each position the TOT counts of all pixels of all frames are summed up. GEMPix data need to be normalized to the delivered dose using the DDS data. Both data acquisitions ran independently, since no trigger to start GEMPix and DDS measurements simultaneously existed. The timing needed to be adjusted offline due to a misalignment between the computer clocks. Figure 6 shows the typical spill structure of the CNAO synchrotron measured with the DDS and the GEMPix.² Data of the GEMPix are shifted coarsely in time to match the DDS data by selecting the time shift leading to the smallest difference between GEMPix and DDS when varying the time shift in 50 ms steps. A finer alignment is not necessary since the two data acquisitions run independently and the set duration of a measurement is 50 ms. After the time alignment, the data follow well the spill structure. Since the GEMPix and DDS measurements are not synchronized, the mean value of the two DDS measurements that are closest in time for each GEMPix frame is calculated, which also reduces the effect of the coarse time alignment. The average of the ratios — GEMPix TOT counts divided by the matching DDS mean value — is calculated for each position. The variance of this average is taken as the best guess for the uncertainty and is approximately a few percent. Only data points with a DDS value above a fixed threshold are taken into account to avoid data at the beginning and at the end of spills, where exact timing is much more important. Figure 7 shows a Bragg curve measured with the GEMPix and compared to the Peakfinder data.³ A more detailed discussion of the results is given in the next section.

A 3D reconstruction of the energy deposition is possible from the same set of data. The average value per pixel per position is calculated and a linear interpolation between positions is used for visualization purposes. Figure 8 shows such a 3D reconstruction.

4 Discussion

Figure 7 shows a quite smooth Bragg curve measured with the GEMPix. However there are significant differences between the GEMPix and the Peakfinder curves, up to 15% for the plateau and peak regions. When matching the GEMPix curve approximately to the Bragg peak of the PTW

²Data shown in figures 6 to 8 are from a single depth scan with carbon ions of 280 MeV/u, which have a nominal range of 150 mm in water.

³The PTW Peakfinder is a commercial product to measure the Bragg curve in water in hadron therapy. It consists of two large area, parallel plate ionization chambers in a sealed watercolumn [15].

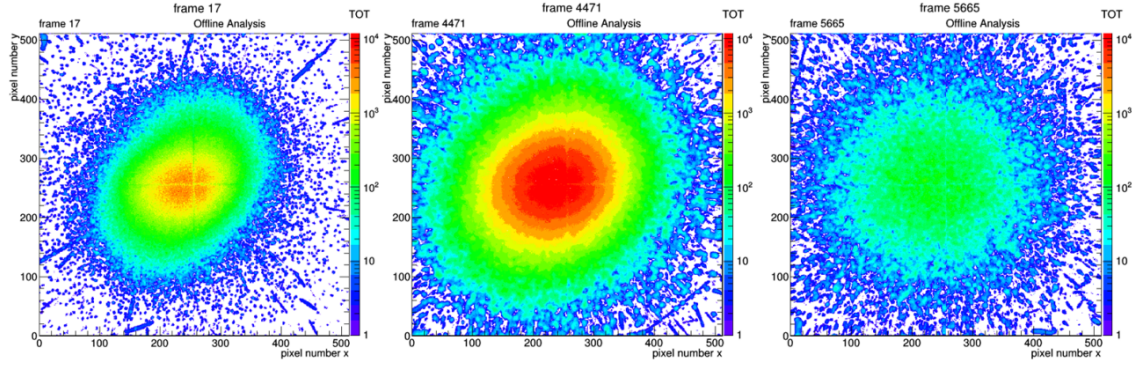


Figure 5. Typical GEMPix 2D images representing the deposited energy for each pixel. The images were acquired at the beam entrance (left), the Bragg peak region (centre) and the tail (right) for 332 MeV/u carbon ions. x and y axes are labelled in units of the pixel number and therefore the spatial coordinates of the readout. Since a pixel is $55 \times 55 \mu\text{m}^2$ large, the total imaging area is $2.8 \times 2.8 \text{ cm}^2$. The TOT counts are colour coded on a logarithmic scale (colours available online). The deposited energy is proportional to the TOT counts.

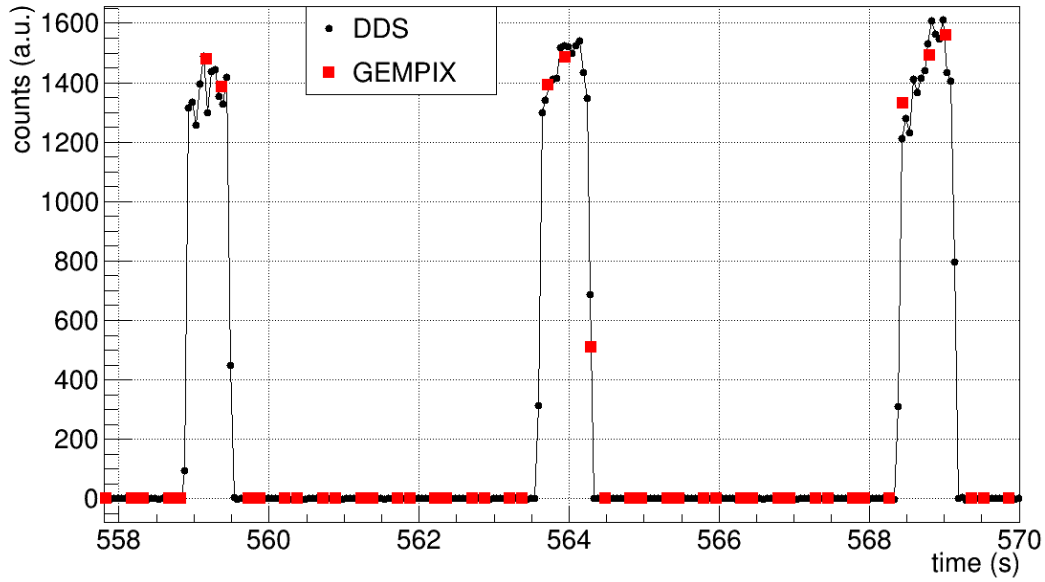


Figure 6. The time structure shows that the GEMPix measurements follow well the spill structure of the reference DDS measurements. The time between two GEMPix measurements alternates between two values since pixels are reset every second frame acquisition, which produces a larger dead time. The time is given in seconds from the beginning of the scan.

Peakfinder measurements by a scale factor as done for figure 7,⁴ there are three main differences to be noticed: in the entrance region and in the tail the GEMPix underestimates the deposited energy while it overestimates at approximately 14 cm depth. The Bragg peak seems also slightly wider.

⁴Since the GEMPix measurement is only a relative measurement, any other normalization is also possible and the choice of normalization is somewhat arbitrary.

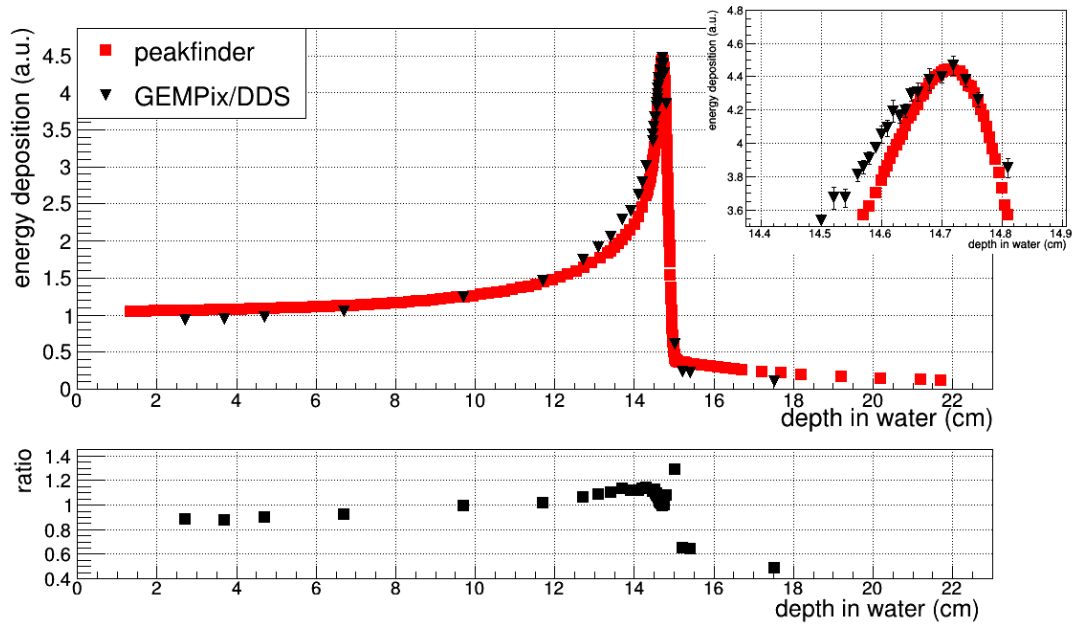


Figure 7. Bragg curve measured with the GEMPix compared to the reference Peakfinder data (upper plot) with a zoom to the Bragg peak region (inlet in upper plot). In the peak and in the entrance plateau the curves differ by maximum 15%, while the difference is larger for the tail (lower plot). The peak is some 3 mm in front of the nominal range of 150 mm due to the energy loss in the two Ripple Filters in the beam line used to enlarge the Bragg peak.

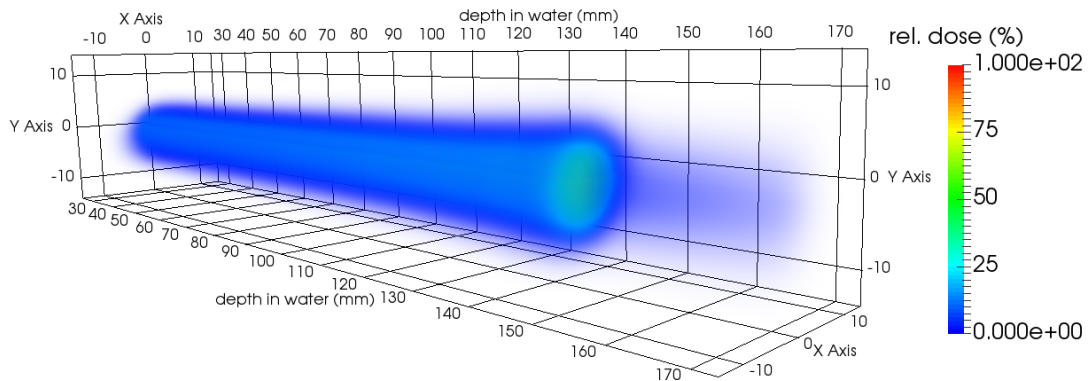


Figure 8. 3D reconstruction of the energy deposition. The Bragg peak at a depth of around 147 mm in water, the spread out of the beam from the entrance point towards the Bragg peak and the tail produced by the fragments are well visible (colours available online).

Several reasons have been investigated:

- The main effect on the Bragg curve is related to the readout of the GEMPix. Measurements of the current driven by the GEMs while performing a depth scan at CNAO also provide a

measurement of the Bragg curve: the current driven by the applied HV between the third GEM and the readout ASIC is proportional to the electrons multiplied in the GEMs. These measurements matched well the reference Bragg curves except for an underestimation of approximately 10% in the Bragg peak.⁵ Since the setup remains the same, a problem with the pixelated readout is assumed: the large number of pixels results in a relatively small charge per pixel for a single ionizing particle as seen at the edge of the beam. For each single pixel a threshold of about 1000 electrons is applied to cut the intrinsic electronic noise. However the bias introduced by this cut could be non-negligible and is believed to change with increasing depth in water since the beam spreads out. A lower threshold can be applied when a more careful setup procedure is followed, thus reducing this effect.

- In the tail of the Bragg curve an underestimation of the dose is also due to the relatively small GEMPix sensitive area of 8 cm² (2.8×2.8 cm²). Since the beam spreads out while traversing the water phantom, the fraction of the beam that cannot be detected increases with depth. A Monte Carlo simulation using FLUKA [17, 18] showed a loss of at least 25% in the measured region behind the Bragg peak, which reduces the underestimation in the tail to half of the underestimation seen in figure 7. A detailed Monte Carlo simulation is in preparation to understand the effect exactly and, if possible, develop a correction. In the long term it is also planned to develop a version of GEMPix with larger sensitive area.
- An underestimation in the entrance region might be due to the heating of the GEMPix ASIC when starting the DAQ. Test measurements with an ⁵⁵Fe source showed a typical increase of the GEMPix response of up to 5% within the first 10 minutes after starting a measurement. Since the Bragg curve is always measured from the smallest to the largest depth, the systematically lower temperature in the beginning of a depth scan could lead to an underestimation of the deposited energy at small depths. The TOT counts of the GEMPix correlate with the temperature and a correction can be applied [11]. Another option would be to cool the readout.
- The Peakfinder uses two ionization chambers vented to air. The stopping power and the dependence of the stopping power on the primary particle energy is therefore different compared to the GEMPix, which is a detector of much different design and uses Ar:CO₂:CF₄ as filling gas. This effect was measured to lead to approximately 4% underestimation in the Bragg peak when using an Argon filled detector compared to using an air filled one for 270 MeV/u carbon ions, while being smaller when using an Ar:CO₂ gas mixture [19]. An effect of similar size in the Bragg peak is obtained when using SRIM [20] to calculate the expected difference for the Ar:CO₂:CF₄ gas mixture.
- Fluctuations between data points might be due to the timing between GEMPix and the reference measurements with the DDS. As explained above, the timing is adjusted offline. In the future this problem will be solved by a triggerable reference measurement with a dedicated ionization chamber. Preliminary results show statistical uncertainties of 1%.

⁵For the stated number the effect due to the smaller sensitive area has been taken into account. This test measurement is useful to disentangle effects from the readout and the GEMs but provides no 2D information.

If all these improvements are implemented it is believed that the GEMPix will be able to measure the Bragg curve with small statistical fluctuations and good agreement with the reference curve as it has been achieved in test measurements analysing the GEM currents except for a 10% underestimation in the Bragg peak. This difference can be partially explained by the stopping power of the used gas mixture.

5 Conclusions and outlook

It has been shown that the GEMPix is capable of measuring the 3D energy deposition of a carbon ion beam in a water phantom. 2D images of the beam, the Bragg curve and the 3D reconstructed energy deposition can be obtained in a single depth scan that lasts about 15 minutes. The results demonstrate the capability of the GEMPix in terms of proof-of-principle. However, there are mismatches between the Bragg curve measured with the GEMPix and the results of the PTW Peakfinder. A new, integrated system consisting of a dedicated water phantom housing the GEMPix and provided with a reference ion chamber installed on the entrance window is currently being built. It will allow to perform measurements independent of the DDS of the therapy centre. Other improvements like a temperature correction and lower threshold settings will be implemented. Since quality assurance and patient treatment plan verification measurements are usually performed at beam intensities up to the maximum available intensity the GEMPix will be also tested at larger beam intensities.

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